Analysis of the State-of-Art Telescopes: Hubble Space, FAST and EHT

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Abstract: As a matter of fact, telescopes are widely utilized in cosmology and astrophysics' observations in recent years. Various ambitious schemes for the telescopes are proposed and constructed with large size and high accuracy. With this in mind, this study systematically analyses three among the most well-known telescopes, i.e., the Hubble space Telescope, the Five Hundred Meter Aperture Spherical Telescope as well as the Event Horizon Telescope. To be specific, the components, structures and functions of the three typical telescopes are evaluated and introduced. At the same time, the advanced results observed in recent years by the facilities are also demonstrated, including the observations of black holes from EHT. According to the analysis, the current drawbacks for these facilities as well as the future developments for the telescopes fields are demonstrated and discussed. Overall, these results shed light on guiding further development of various telescopes as well as pave a path for further exploration of cosmology and universe.

1 INTRODUCTION

Telescopes have always been a significant instrument in the universe. Ever since Galileo pointed his small telescope towards the sky in 1609, telescopes have greatly expanded the knowledge of the space (Williams et al., 1996). Larger telescopes are required for astronomers to see very remote and feeble sources of light because they gather more light. Therefore, building large telescopes has become crucial for most of the astronomical discoveries (Freedman et al., 2001). For instance, the Hubble Space Telescope (HST) was launched in 1990 to provide much better insights into stars, galaxies, and the rate of expansion of the universe (Riess et al., 2022). Images taken by Hubble were very sharp which enabled scientists to measure distances accurately which in turn revealed that the universe is expanding at a rate faster than expected (Riess et al., 2022).

Over the last few years, several important telescope projects have made considerable progress. The James Webb Space Telescope (JWST), launched at the end of 2021, began to produce science in 2022 (Astro2020 Decadal Survey, 2021). The JWST with a 6.5-meter mirror Observes mainly in infrared wavelengths which means that astronomers can look at parts of the sky that are not observable with previous telescopes. It has also provided pretty good images of galaxies, star formation, and even the atmospheres of exoplanets. These observations are contributing to the knowledge of the early universe and the search for life in the universe (Astro2020 Decadal Survey, 2021).

Another large project currently under development is the Square Kilometre Array (SKA), which will be the world's largest radio telescope. The SKA's antennas are situated in Australia and South Africa, and will be deployed such that they cover an area of one square kilometre (Wedemeyer et al., 2024). It will be able to pick up very faint radio signals and enable scientists to investigate the state of the universe right after the Big Bang. It will also solve problems like dark matter, dark energy and galaxy formation (Wedemeyer et al., 2024).

Alongside the space and radio telescopes, optical telescopes are being built to be very large ground-based telescopes. The European Extremely Large Telescope (ELT) with a mirror of 39 meters in diameter will increase the sensitivity to weak signals from the celestial objects by a factor of 39 (European Southern Observatory, 2022). The ELT is predicted to assist in the finding of Earth like planets around other stars and the formation of galaxies and stars. Another telescope which is still under development is the Atacama Large Aperture Submillimeter

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Telescope (AtLAST) which is being developed to observe stars and the sun at submillimeter wavelengths. AtLAST will give new insights into the stellar activity and the solar atmosphere and will contribute to the knowledge of stellar formation and evolution (Wedemeyer et al., 2024).

This paper is motivated by the recognition of the importance of large telescopes in astronomy. These powerful tools enable scientists to probe phenomena that were heretofore unproblematized, solving long standing mysteries while raising new questions about the universe. For this, the paper is arranged as follows: First, it defines what a telescope is, how it works and what are the main types of telescopes, thus providing the reader with a proper introduction. Second, it lists the major applications of telescopes in astronomy and emphasizes their role in science breakthroughs. Third, the paper gives a detailed description of three specific telescopes: Hubble Space Telescope, China's FAST radio telescope, and the Event Horizon Telescope (EHT). It outlines what makes them special, what contribution they have made to science and how they have enriched the knowledge of the cosmos. Finally, the paper outlines some current limitations of telescope technologies, and looks ahead to future developments, which could revolutionize astronomy and how one will study the universe. In this framework, the paper aims to argue for the need to continue to invest in the development of telescopes because these extraordinary machines help people to understand the universe better.

2 DESCRIPTIONS OF TELESCOPES

Astronomers use telescopes to view objects in space by collecting and focusing electromagnetic radiation, which includes visible light, infrared radiation, and radio waves (Gardner et al., 2006). In general, telescopes work by gathering more radiation than the human eyes can gather and focusing it into a clear and distinct image. The two primary principles through which telescopes work are refraction and reflection. Refracting telescopes use lenses to bend and focus the incoming light while reflecting telescopes use mirrors to collect and reflect radiation to a focal point. Adapting to today's large telescopes, mirrors are used as these can be made to be much larger and more efficient than lenses enabling astronomers to see very faint and very distant cosmic objects (Gardner et al., 2006).

Based on the kind of electromagnetic radiation they detect, telescopes are also classified. Optical telescopes, such as the Hubble Space Telescope, observes visible light, and they are used by astronomers to study galaxies, stars, and planets. The James Webb Space Telescope (JWST) is an infrared telescope that detects infrared radiation from objects too faint, too cool, or too distant to see with visible light alone (Gardner et al., 2006). Thus, infrared telescopes are quite crucial in the study of early galaxy formation, star formation processes and exotic planets in other solar systems. Another major type is radio telescopes, which capture radio waves from space using large antennas or antenna arrays. The Square Kilometre Array (SKA) will detect extremely weak radio signals from distant cosmic phenomena (Cordes, 2009). Radio telescopes allow astronomers to study exotic objects such as pulsars, quasars, and black holes, as well as explore the large scale structure and evolution of galaxies.

The specific scientific objectives of different telescopes are determined by their observational potential. Optical telescopes have mainly contributed to the advancement of the knowledge of stellar properties, galaxy structures and planetary systems round other stars. They are important in understanding formation of stars, early universe conditions and organic molecules (that may be an indicator of life) by observing through cosmic dust clouds. Black holes, fast changing cosmic events, and the physics of extreme environments are examined through mapping of cosmic background radiation (Cordes, 2009).

In conclusion, of all the types of telescopes, modern astronomy would not be complete without them, and they are an indispensable tool in acquiring the necessary information that helps shape the understanding of the universe. The continuing innovation in telescope technology holds the key to new discoveries and a more profound understanding of cosmic questions that remain unresolved (Gardner et al., 2006; Cordes, 2009).

3 HUBBLE SPACE TELESCOPE

The Hubble Space Telescope is one of the greatest achievements in astronomy and is one of the most useful telescopes of the modern world. Launched in 1990, Hubble soars above the atmosphere, giving it an unparalleled capacity to gather detailed images of faraway objects without the blur caused by the atmosphere (Williams et al., 1996). It has a primary mirror that is 2.4 meters in width, a few smaller secondary mirrors, and a number of scientific instruments that detect visible and ultraviolet light. When objects in the distance shine or reflect light, the radiation travels through space and strikes Hubble's primary mirror, which then reflects the light to a smaller secondary mirror. The secondary mirror then forms an image at the scientific instruments which produce a sharp image or analyse the nature of the object (Freedman et al., 2001).

The primary objectives of Hubble are to learn about stars, galaxies, planets, and other objects in the sky. It has scanned more than 1,000 galaxies, stars in various states of their existence, planets in the solar system and planets around other stars. This is remembered for the "Hubble Deep Field" where Hubble was turned to an apparently starless part of the sky for many hours. Fig. 1 shows more than 3,000 galaxies, some up to fthe billion light-years away, a gold mine for scientists to understand how galaxies form and how the universe evolves (Williams et al., 1996).

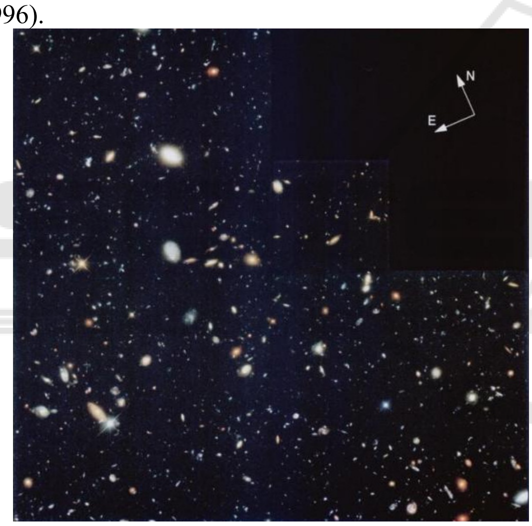

Figure 1: A color composite image of the full HDF field, constructed from the F450W, F606W, and F814W images (Williams et al., 1996).

Hubble has kept on finding out new things in the recent past. This is because it has made a major discovery on the Hubble constant, which is a measure of the rate of the expansion of the universe. For this purpose, Hubble has been used to measure the cosmic distances using a type of star known as Cepheid variables. These latest measurements are inconsistent with the earlier theories, and this suggests that the universe is expanding more rapidly than it should. This discrepancy, termed the "Hubble tension," suggests that there is some new physics out there that is not yet incorporated into the models (Riess et al., 2022).

One of the most significant recent discoveries made by Hubble is the existence of a distant star called Earendel, which is about 12.9 billion light-years away. It is a single star at such a great distance that it is too dim to be detected directly. Nevertheless, Hubble did it by taking advantage of a natural magnifying effect known as gravitational lensing, which is caused by massive galaxies along the line of sight to Earendel. The discovery of Earendel gives a rare opportunity to study stars from the early universe and teach us about how they were born after the Big Bang (Welch et al., 2022). These are just some of the recent discoveries that highlight the continued relevance of the Hubble Space Telescope. Hubble was designed to be a well-built machine with a simple working mechanism and excellent observing system to enable scientists understand some of the most important issues concerning the cosmos.

4 FIVE-HUNDRED-METER APERTURE SPHERICAL RADIO TELESCOPE

The Five Hundred Meter Aperture Spherical Telescope (FAST), also referred to as the "China Sky Eye", is currently the largest single dish radio telescope in the world. Situated in Guizhou Province of China, FAST started full operation in 2020 and has greatly enlarged the horizon of human vision in the radio frequency region (Li et al., 2021). The telescope has a 500 meter wide spherical mirror which is made of more than 4000 mutually movable aluminum panels. Unlike the normal fixed dish antennas, the panels of FAST are able to change their configuration in real time to generate a smaller and much more accurate parabolic surface of about 300 meters in diameter. This flexibility enables FAST to capture celestial objects over a wider angle of the sky without having to move the entire dish physically (Han et al., 2021).

FAST works by picking up radio waves from far away cosmic objects. The incoming radio signals reflect on the large mirror and are focused on to a platform receiver cabin which is suspended 140 meters above the dish. This cabin contains the receiver elements that are sensitive to the incoming signals and translate them into a form that can be used for scientific analysis. Due to the fact that radio waves from distant objects are very weak in intensity, it is FAST's large collecting area that enables it to detect very weak signals which other smaller telescopes cannot resolve well (Li et al., 2021).

The fast pulsars, FRBs and neutral hydrogen gas in distant galaxies are the main objects of research for astronomers with the help of FAST. Pulsars are compact stellar objects whose cores are neutron stars that pulse out radioactive signals. FRBs are high energy pulses of radio waves whose source lies outside the galaxy. In analyzing the neutral hydrogen gas, FAST enables investigators to determine how galaxies have been created and transformed. This makes it easy for FAST to look for signs of intelligent extraterrestrial life through radio signals (Kang et al., 2022).

It has been not so long ago that FAST has started its work and already it has brought much research output. One significant finding is the detection of a large number of repeating pulses from the fast radio burst FRB 121102. Within an observation period of about 60 hours spread over several weeks, FAST was able to identify more than 1,600 pulses from this source. This discovery gave insights into the energy content and the nature of FRBs and thus did not support the earlier theoretical predictions which suggested that the bursts are due to low efficiency, high energy processes (Li et al., 2021).

Recently, there was another success, and it was FAST's precise observation of another repeating burst, FRB 20201124A. Within two months of observation, FAST observed about 1,800 bursts from this object, which displayed some surprising behavior in the polarization of the radio signal. This showed that FRB 20201124A occurs in a medium with dynamically evolving magnetic fields, which could mean that it is associated with an X-ray binary or even a magnetized stellar remnant. These observations have helped to refine the knowledge of the process and the environment of FRBs (Xu et al., 2022). Successful surveys of neutral hydrogen gas have also been done by FAST and hence new galaxies found. These are so called "dark galaxies" which are rich in gas but almost devoid of stars and therefore are impossible to detect with optical telescopes. This discovery gives important information on the early formation and the subsequent evolution of galaxies (Kang et al., 2022).

5 THE EVENT HORIZEN TELESCOPE

The Event Horizon Telescope (EHT) is not a single telescope, but a network of radio telescopes spread around the globe. These telescopes work together to observe space at very short radio wavelengths. EHT creates a virtual telescope as large as the Earth itself by combining observations from multiple telescopes. Through Very Long Baseline Interferometry (VLBI) astronomers obtain outstanding resolution power to detect details beyond the capabilities of individual telescopes (Event Horizon Telescope Collaboration, 2019).

The Event Horizon Telescope (EHT) functions through coordinated observations of the same celestial object from various positions on Earth's surface. The participating telescopes independently capture radio wave data from distant astronomical objects. Scientists store the collected observations with atomic clock-synchronized time information. Scientists use powerful computers to merge data from all telescopes after observations finish which results in detailed images of the observed objects. The Event Horizon Telescope uses its ability to observe black hole event horizons to study environments near these objects where gravity traps all light (Event Horizon Telescope Collaboration, 2019).

EHT's main scientific goal is to observe and image black holes, particularly their event horizons. Black holes are among the most enigmatic objects in the universe, and their intense gravity affects the surrounding matter and radiation. Observing black holes directly allows EHT to help scientists test Einstein's General Relativity theory in the most extreme gravitational conditions (Doeleman et al., 2008).

EHT has obtained remarkable outcomes in its recent operations. Scientists from the collaboration published the world's first direct image of a black hole which resides at the center of Messier 87 (M87) in 2019. Scientists observed a bright ring structure with a dark central shadow through their instruments which confirmed predictions from Einstein's theory. The "black hole shadow" appears as a dark area because the black hole's intense gravity traps all incoming light. The ring of light surrounding the shadow emerges from hot gas particles which orbit near the black hole and produce radio waves before reaching the event horizon as depited in Fig. 2 (Event Horizon Telescope Collaboration, 2019).

The Event Horizon Telescope (EHT) achieved another major milestone in 2022 by revealing the first-ever direct visual evidence of Sagittarius A* (Sgr A*) which serves as the supermassive black hole located at the Milky Way's center. Scientists observed a dark shadow surrounded by a bright ring of hot gas in the same manner as the M87 black hole image. The second direct observation proved that black holes of any size follow identical behavior according to

Einstein's theory of gravity (Event Horizon Telescope Collaboration, 2022).

EHT has also studied the magnetic fields around black holes. Polarized light observations of M87's black hole showed that there are strong magnetic fields around the event horizon. These magnetic fields are very important in determining the powerful jets of material that are ejected from black holes. Knowing these jets assist astronomers in understanding how black holes affect their host galaxies (Event Horizon Telescope Collaboration, 2021).

EHT has made these discoveries which have greatly enhanced the understanding of black holes. They show how human collaboration and advanced technology can tackle some of the universe's deepest mysteries, bringing previously invisible phenomena clearly into view.

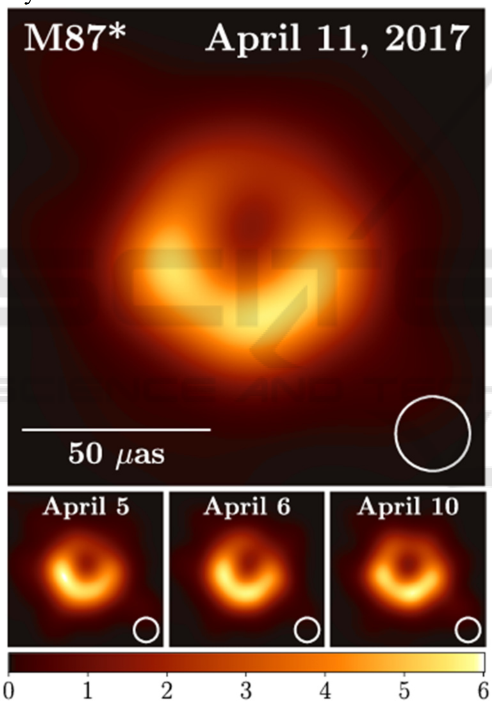

Figure 2: First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole (Event Horizon Telescope Collaboration, 2019).

6 COMPARISONS

Different telescopes operate today with their own distinct advantages and limitations. The Hubble Space Telescope along with other optical telescopes use visible light to produce precise images of distant galaxies stars and planets. The study of galaxy formation and universe expansion rates became possible through their observational capabilities (Williams et al., 1996; Riess et al., 2022). The telescopes struggle to detect objects which are obscured by space dust clouds. The instruments lack sufficient ability to observe young stars and galaxies that are blocked by dense dust clouds. The large size of FAST allows it to detect signals which optical telescopes cannot detect. The instrument has revealed numerous enigmatic radio bursts together with galaxies which were previously undetectable (Li et al., 2021; Zhu et al., 2022). Radio telescopes lack the capability to produce precise detailed images which optical telescopes achieve. The images produced by these instruments tend to have reduced resolution which hinders researchers from studying tiny details.

The Event Horizon Telescope (EHT) combines multiple radio telescopes to see extremely small details. It captures clear images of black holes, something no other telescope can do. For example, EHT recently took the first pictures of black holes and showed us what they really look like (Event Horizon Telescope Collaboration, 2019; 2022). Nevertheless, EHT can only observe very few objects, mostly black holes, because its observations are complicated and need telescopes around the world to cooperate at exactly the same time.

Telescopes continue to face certain restrictions despite their achievements. The atmosphere above Earth prevents telescopes from Earth from making complete observations. Space-based telescopes eliminate this problem yet their high cost and challenging maintenance requirements make them difficult to operate. The current generation of telescopes restricts scientists from observing objects that are either too faint or too distant.

In the future, new telescopes might solve many of these problems. Scientists are building bigger telescopes on Earth, using special techniques to get clearer pictures. New space telescopes like JWST will observe infrared light, helping us see objects hidden behind dust clouds (Gardner et al., 2006). New radio telescope arrays like the Square Kilometer Array (SKA) will become even more sensitive, letting us discover things in the universe one can't imagine today (Cordes, 2009).

7 CONCLUSIONS

To sum up, the exploration of the universe depends heavily on large telescopes for scientific discovery. This paper explained the fundamental principles of telescopes by describing their operational mechanisms and different types and functional applications. The Hubble Space Telescope together with FAST and the Event Horizon Telescope represent three essential telescopes in this discussion. Through its clear images of distant galaxies Hubble Space Telescope enabled scientists to study universal expansion patterns. Scientists used FAST to detect radio signals from space objects which led to the discovery of new galaxies and unexplained radio bursts. The Event Horizon Telescope produced authentic black hole images which enabled scientists to verify fundamental gravity principles. The current limitations of telescopes include Earth's atmospheric interference together with challenges in detecting faint objects. The JWST and SKA telescopes represent upcoming technological advancements which will eliminate various current problems thus enabling deeper space observation. The research holds significance because advanced telescopes will enable humans to solve basic questions about the cosmic origins and universal operations. The ongoing development of telescopes will enable us to discover new universe information for multiple future years.

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